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CHIRAL DYNAMICS, STRUCTURE OF $\Lambda(1405)$, AND $\bar{K}N$ PHENOMENOLOGY

TETSUO HYODO

*Physik-Department, Technische Universität München, D-85747 Garching, Germany, and
 Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
 thyodo@ph.tum.de*

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We investigate the structure of the $\Lambda(1405)$ resonance and $\bar{K}N$ phenomenology in the perspective of chiral SU(3) dynamics. Utilizing the chiral coupled-channel approach which well describes the $\bar{K}N$ scattering observable, we perform three different analyses to clarify the structure of the $\Lambda(1405)$ resonance. The results consistently indicate the meson-baryon molecule picture of the $\Lambda(1405)$. We argue the consequence of the chiral dynamics in $\bar{K}N$ phenomenology and the antikaon bound state in nucleus, emphasizing the important role of the strong $\pi\Sigma$ interaction.

1. Introduction

The $\Lambda(1405)$ is a negative parity excited baryon with strangeness $S = -1$. It is well known that simple constituent quark models have a difficulty in describing the light mass of the $\Lambda(1405)$, in spite of the successful description of other excited baryons. On the other hand, the $\Lambda(1405)$ can be reasonably described by the coupled-channel framework of meson-baryon scattering. These observations have caused a long-standing discussion about its structure. A recent interest on this particle is related to the $\bar{K}N$ interaction below the threshold. It should be noted that the subthreshold $\bar{K}N$ amplitude cannot be directly observed in experiments since it is kinematically forbidden. The only way to access this region is given by the spectrum of the coupled-channel $\pi\Sigma$, which is largely dominated by the $\Lambda(1405)$ resonance. Therefore the property of the $\Lambda(1405)$ is related to the $\bar{K}N$ interaction below threshold, which is an essential building block for the study of kaonic nuclei. Here we report on recent development of chiral SU(3) dynamics about these issues: the structure of the $\Lambda(1405)$ and its consequence in $\bar{K}N$ phenomenology.

2. Nonperturbative chiral dynamics

We utilize the chiral coupled-channel approach, which describes hadron scatterings and resonances, incorporating two important principles: (i) the interaction follows

the low energy theorem of chiral symmetry,¹ and (ii) the amplitude should be constrained by the unitarity condition in coupled channels.² In practice, we determine the low energy interaction by the leading order term of chiral perturbation theory:

$$V_{ij} \sim -\frac{C_{ij}}{4f^2}(\omega_i + \omega_j), \quad (1)$$

where C_{ij} are the coupling strengths, f is the meson decay constant, and ω_i is the energy of the meson in channel i . The coupled-channel scattering amplitude T_{ij} is given by solving the Bethe-Salpeter (BS) equation

$$T_{ij} = V_{ij} + V_{il}G_lT_{lj}, \quad (2)$$

where G_i is the loop function. Applied to the $S = -1$ meson-baryon scattering system,³ the resulting amplitude well reproduces the experimental data such as total cross sections of K^-p scattering, threshold branching ratios, and the invariant mass spectrum in $\pi\Sigma$ channel. The framework has been successfully applied also to the $S = 0$ sector with nucleon resonances, to mesonic sectors, and to systems including heavy quarks in the target hadrons. These successes in variety of systems indicate the importance of the above two principles (i) and (ii) when constructing the hadron scattering amplitude.⁴

3. Structure of the $\Lambda(1405)$ resonance

We first analyze the structure by paying attention to the renormalization procedure. Based on a general ground of the scattering theory, origin of resonances can be classified into two categories: dynamical state and Castillejo-Dalitz-Dyson (CDD) pole contribution.⁵ The dynamical state is the resonance generated by the two-body interaction, which is regarded as a two-body molecule state. The CDD pole is considered to be an elementary or independent particle, which has the origin outside the model space of the scattering. In the present case of the $\Lambda(1405)$, the CDD pole contribution would come, for instance, from three-quark state. The previous studies of the chiral coupled-channel approach have shown that CDD pole contribution is introduced in several ways to the interaction kernel V_{ij} in Eq. (2). In a recent work,⁶ it is pointed out that the CDD pole contribution can also exist in the loop function G_i through the renormalization procedure. It has been explicitly shown that a certain choice of the cutoff parameter introduces the pole term contribution in V_{ij} , even if the CDD pole contribution is not included in the beginning. Analyzing the two examples, $N(1535)$ resonance in πN scattering and $\Lambda(1405)$ resonance in $\bar{K}N$ scattering, it is found that a substantial CDD pole contribution is required for the $N(1535)$ on top of the dynamical component, while the $\Lambda(1405)$ is largely dominated by the dynamical component.

Next we consider the scaling with respect to the number of colors N_c , which is a powerful tool to investigate the quark structure in hadron effective theory. The key issue is that, in QCD, the N_c dependences of the hadronic quantities are known from the general argument.⁸ Therefore, introducing the N_c dependence into the

Table 1. Schematic classification of the results of the analyses for the structure of the $\Lambda(1405)$. Components q , M , and B stand for quark, meson, and baryon, respectively.

Components	qqq	MB	other components ($qqqq\bar{q}$, MMB , ...)
Ref. 6 (CDD pole)		likely	
Refs. 9 (N_c scaling)	not likely		
Ref. 10 (charge radius)	not likely		

framework and analyzing the properties of the resonance with respect to N_c , we can extract the information of quark structure of the resonance.⁷ In contrast to the mesonic sector, baryonic sector contains the nontrivial N_c dependence in the leading order WT interaction.⁴ Introducing all the N_c dependences in the model, the scattering amplitude is calculated as a function of N_c . The general argument tells us that if the excited baryon is a three-quark state, the mass is proportional to N_c and the width should be a constant [$\Gamma \sim \mathcal{O}(1)$]. The result shows that the width of the $\Lambda(1405)$ resonance changes when the N_c is increased.⁹ This is a clear indication of the non- qqq structure of the $\Lambda(1405)$ resonance.

Finally we study electromagnetic properties of the $\Lambda(1405)$ resonance by introducing an external photon field.¹⁰ Because the resonance is expressed by the bubble sum of the meson-baryon loops, the photon field is attached to the constituent mesons and baryons. In order to extract the information of size, we evaluate the electric mean squared radius by neglecting the decay channels. The result turns out to be about 2 fm^2 with negative sign. This means that the electromagnetic size of this resonance is much larger than the ground state nucleon, which is mainly composed of three-quark state. Hence the result is consistent with the picture of the $\Lambda(1405)$ that the K^- is widely spread around the proton.

To summarize the above results, we list the possible quark and hadronic components of the $\Lambda(1405)$ in Table 1. For an ordinary baryon, the main component would be the three-quark state (qqq). The existence of the meson-baryon component (MB) in baryonic system is also known, for instance, by the pion cloud in the ground state nucleon. There could be further contribution from other components on top of qqq and MB . Note that we distinguish the meson-baryon state MB from five-quark state $qqqq\bar{q}$; the former is a combination of two color singlet hadrons, while the latter is defined as a totally color singlet five-quark state which has no overlap with the MB state.⁶

The analysis of renormalization procedure⁶ implies that the $\Lambda(1405)$ resonance is dominated by the MB dynamical component. The result of the N_c scaling⁹ indicates that the three-quark component of the $\Lambda(1405)$ is small, although we cannot specify the explicit origin of the resonance by itself. The study of the electromagnetic properties¹⁰ shows that the size of the $\Lambda(1405)$ is larger than the ordinary baryons. It is remarkable that all three different analyses are consistent with the dominance of meson-baryon molecule structure of the $\Lambda(1405)$.

4. Effective $\bar{K}N$ interaction and kaonic nuclei

The possible antikaon binding in nucleus was discussed in Refs. 11 using phenomenological $\bar{K}N$ interaction. It was argued that the strong $\bar{K}N$ attraction would cause many interesting phenomena in kaonic nuclei. Stimulated by recent experimental searches, this topic is now lively discussed. Since we have a theoretical framework of chiral dynamics, which reproduces the experimental data of $\bar{K}N$ scattering quite well, it is natural to ask what chiral dynamics tells us about the kaonic nuclei.

For this purpose, an effective single-channel $\bar{K}N$ potential is derived in chiral dynamics,¹² which enables a standard variational calculation of the few-body kaonic nuclei. The strategy is as follows: (a) we transform the original coupled-channel framework into the single channel problem, and (b) we construct an equivalent potential to be used in the Schrödinger equation of single channel. In step (a), the effect of the $\pi\Sigma$ channel is included in the single-channel effective $\bar{K}N$ interaction within an exact transformation. Step (b) requires a local approximation for the potential in coordinate space, but we impose the constraint that the potential should reproduce the scattering amplitude of chiral coupled-channel approach.

In this way we construct an effective $\bar{K}N$ potential, which incorporates the dynamics of $\pi\Sigma$ and reproduces the scattering amplitude in chiral dynamics. The strength of the attraction turns out to be about a half of the phenomenological potential of Refs. 11. Indeed, the variational calculation of K^-pp system with this potential shows a small binding energy of about 20 MeV.¹³ Let us consider the reason for the weaker interaction.

Actually the consequence of the weaker attraction is seen in the two-body scattering amplitude.¹² The resonance position in the $\bar{K}N$ amplitude appears at around 1420 MeV, not at the nominal position of 1405 MeV. Since the binding energy measured from the $\bar{K}N$ threshold is reduced to 15 MeV, the effective $\bar{K}N$ interaction is less attractive. The shift of the resonance energy is the key to determine the strength of the attraction. Note that the $\pi\Sigma$ amplitude, which corresponds to the observed spectrum, shows the resonance structure at around 1405 MeV.

The difference between the resonance positions in the $\bar{K}N$ and $\pi\Sigma$ channels was discussed in Ref. 14. It turns out that there are two poles for this resonance, and the poles couple to the $\bar{K}N$ and $\pi\Sigma$ states with different weights, so that the spectrum differs each other. In Ref. 12, it is pointed out that the diagonal couplings in Eq. (1) are attractive enough to generate singularities of scattering amplitude in both $\bar{K}N$ and $\pi\Sigma$ channels ($C_{\bar{K}N} = 3$ and $C_{\pi\Sigma} = 4$). This is in contrast to the phenomenological potential,¹¹ where the diagonal $\pi\Sigma$ interaction is set to be zero. The strong $\pi\Sigma$ attraction in chiral dynamics eventually reduce the strength in the equivalent local $\bar{K}N$ potential. The coupling strengths in Eq. (1) are strictly governed by the flavor SU(3) symmetry and this feature is also shared with the traditional coupled-channel approach by Dalitz.²

From a schematic viewpoint, the phenomenological potential¹¹ describes the $\Lambda(1405)$ as a Feshbach resonance: quasibound $\bar{K}N$ state embedded in the $\pi\Sigma$ con-

tinuum. In the chiral scheme, the driving force to generate the $\Lambda(1405)$ is the attraction in the $\bar{K}N$ channel, while the $\pi\Sigma$ system is also strongly and attractively interacting. As a consequence, effective $\bar{K}N$ interaction is less attractive than the phenomenological one, in order to achieve the same spectrum of the $\Lambda(1405)$.

5. Conclusions

We have reviewed some recent development in chiral SU(3) dynamics related to the $S = -1$ meson-baryon scattering. Within the present framework, we find that the structure of the $\Lambda(1405)$ is dominated by the meson-baryon molecule component. The effective $\bar{K}N$ interaction turns out to be less attractive than the phenomenologically constructed one, because of the strong $\pi\Sigma$ dynamics constrained by chiral SU(3) symmetry.

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